DOI: 10.54254/2753-8818/92/2025.21264

Advances in Heat Transfer Composites: A Comprehensive Review of Materials, Properties and Applications

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Abstract: In the wake of modern technology's continuous evolution, thermal transfer compositions have emerged as crucial materials for optimizing heat management across diverse fields, including electronics, energy, and automotive sectors. This review zeroes in on the research progress of thermal transfer compositions, methodically exploring aspects such as material selection, performance optimization, and application prospects. Grounded on this, it analyzes the selection of heat conductive fillers, the requisites for matrix materials, and the impact of interface effects from the perspective of materials science while also introducing advanced design and preparation technologies. Furthermore, through specific case analyses, it vividly showcases the practical application effects of thermal transfer compositions in areas like electronic product heat dissipation heat management of new energy vehicle batteries, and efficiency enhancement of solar photovoltaic panels. Eventually, it pinpoints the current challenges, namely interface compatibility, long-term stability, and cost-effectiveness, and peers into future research directions, emphasizing the importance of new material development, advanced manufacturing technologies, and interdisciplinary integration. Research findings suggest that thermal transfer compositions not only significantly improve the heat management performance of systems but also promote sustainable development and technological innovation, thus harboring extensive application potential and development prospects.

Keywords: Thermal transfer, composition, thermal conductive materials, thermal management, review

1. Introduction

With the continuous growth of modern society's demand for efficient energy utilization and environmental protection, thermal management technology has become an indispensable part of numerous industrial and technological fields. Against this backdrop, thermal transfer composites have surfaced as an innovative solution. Through the integration of high thermal conductivity materials with other functional components, these composites display excellent thermal conduction, convection, or radiation characteristics, thereby substantially enhancing the heat dissipation efficiency and operational effectiveness of various devices. Despite the fact that thermal transfer compositions have achieved numerous milestones, this field remains beset with a multitude of challenges. On one hand, as device sizes continue to shrink and integration levels rise, traditional cooling methods often fail to

DOI: 10.54254/2753-8818/92/2025.21264

meet increasingly stringent requirements. On the other hand, the protracted development cycles and high costs associated with new materials limit their widespread application. Therefore, it has become a necessary part of having a thorough understanding of thermal transfer mechanisms, exploring new material systems, and developing efficient preparation processes. In view of the above context, this review is dedicated to comprehensively reviewing the research progress of thermal transfer compositions, with a particular focus on their material selection, performance optimization, and application prospects. The paper is divided into the following main parts. Firstly, I will briefly review the basic principles of thermal transfer in order to write the following research. Then, I will describe the characteristics of different types of thermal transfer compositions and their selection principles and then summarize the research trends in the existing literature. Finally, this paper will analyze the practical applications of thermal transfer compositions in various fields through specific case studies and provide insights into possible future research directions and development trends.

2. Fundamentals of thermal transfer

The basic principle of thermal transfer is fundamental to understanding how heat moves between different media, and it is carried out through three main mechanisms: conduction, convection, and radiation. At the microscopic level, thermal energy can be regarded as the total kinetic energy of the particles within a substance, like molecules and atoms. When two objects at different temperatures come into contact, the particles of the high-temperature object move more vigorously and transfer some of their kinetic energy to the particles of the low-temperature object through collisions, causing the particles of the low-temperature object to accelerate and the temperature to rise. Therefore, a fundamental form of heat transfer is the direct exchange of molecular kinetic energy.

3. The view of thermal transfer compositions

3.1. The basic concept of thermal transfer composition

The basic concept of thermal transfer compositions can be defined from the point of view of materials science and engineering, and such compositions are designed to optimize the transfer of heat from one object to another. They are commonly used in systems that require efficient heat dissipation or thermal management, such as electronics, machinery, and other industrial applications. It is a class of composite materials that combines different materials in a specific way in order to achieve the goal of higher efficiency in thermal transferring. The compositions can be solid, liquid, or gas, and their performance depends on their material selection, structural design, and preparation processes [1].

3.2. The features of various compositions and its selection principles

Different types of thermal transfer compositions have their own unique physicochemical properties and application scenarios, and choosing the right composition requires a comprehensive consideration of multiple aspects. Firstly, the thermal conductivity is an important measure of a material's ability to conduct heat; for instance, for equipment operating in high-temperature environments like engines or power electronic components, metal-based or ceramic-based compositions with high thermal conductivity are preferred. Secondly, cost-effectiveness is crucial, as thermal transfer compositions should be produced in a manner that meets the performance requirements while keeping production costs as low as possible, such as by using less expensive and readily available raw materials. Moreover, environmental adaptability must be considered as well since the choice of materials has to be adapted to different working environments in view of the long-term stability in use [2].

3.3. Research trends in thermal transfer compositions

In recent years, in tandem with the progression of science and technology and the evolution of market demand, the research on thermal transfer compositions has exhibited several distinct development trends. To begin with, a multi-scale composite structure has come to the fore. In this context, novel composite materials are being developed by integrating optimization designs at both the microscopic and macroscopic scales, with the aim of augmenting the overall performance. Secondly, sustainable development has taken center stage, with an emphasis on researching and developing environmentally friendly materials, reducing harmful substance emissions, and promoting the circular economy. In essence, thermal transfer compositions act as bridges between fundamental research and practical applications and play an irreplaceable role in various high-tech fields. Looking ahead, with the continuous advancement of materials science and technology, it is anticipated that more innovative thermal transfer compositions will surface, presenting new ideas and methods for addressing diverse heat management challenges [3].

4. A list of available thermal transfer compositions

After consulting the information, I found several thermal transfer compositions. Firstly, the widely used thermal transfer compositions currently are refrigerants. Their design takes into account chemical stability, environmental impact, and flow characteristics in heat exchangers to ensure optimal performance in heating and cooling applications. And among these materials, some are worth paying attention to.

A combination of tetrafluoropropene, tetrafluoroethylene, and pentafluoropropene:

The refrigerant composition contains at least approximately 98.5% of the following 3 compounds in mass fraction: 33.0% to 45% difluoromethane (HFC-32), 48.5% to 67.0% 2,3,3,3-tetrafluoropropylene (HFO-1234yf), and 1.0% to 6.0% fluor ethane (HFC-161). This heat exchange system includes air conditioning, refrigeration applications, and heat pump applications, and also involves such compounds as alternatives to refrigerants R-410A, R-32, or R-454B for heating and cooling applications.

An environmentally friendly refrigerant containing CO2:

This mixture refrigerant includes a mass fraction of CO2 ranging from 70% to 90% and a mass fraction of 1,1-difluoroethane, propane, fluormethane, propylene, difluoromethane, and 1,1,1-trifluoroethane ranging from 10% to 30%. The mixed refrigerant has the characteristics of 0 ODP and a low GWP value. While meeting the environmental requirements of the new generation of refrigerants, it can be directly charged into the original CO2 system, avoiding the cost increase caused by equipment replacement or system re-optimization. Additionally, due to the lower temperature glide, the system remains stable and does not experience instability caused by component migration, allowing for the direct charging of pre-mixed refrigerant into the system without the need for evacuation or vacuuming.

Composition of HFO-1234yf and HFC-152a:

This composition is an environmentally friendly refrigerant blend that utilizes HFO-1234yf and HFC-152a as refrigerants. The blend has a low GWP, low toxicity, low-flammability, and low temperature glide, and can be used for the thermal management of passenger compartments in hybrid vehicles, mild hybrid vehicles, plug-in hybrid vehicles, or fully electric vehicles (transferring heat from one part of the vehicle to another), thus providing air conditioning (A/C) or heating to the passenger cabin.

R-22 alternative refrigerant compound:

In terms of mass fraction, the composition contains: 0.1%~2% of one or more components selected from (C4~C6) alkanes, (C4~C6) olefins and their mixtures, especially isopentane; 0.2%~20% 1-

DOI: 10.54254/2753-8818/92/2025.21264

chloro-3,3,3-trifluoropropylene; 1%~19% 1,1,1,2,2-pentafluoroethane; 35%~90% 1,1,1,2-tetrafluoroethane; 5%~30% difluoromethane. This invention also relates to the use of the compound as a refrigerant, refrigerant systems, and refrigeration methods using this compound.

Fluoropolymer binder coatings used in electrochemical devices:

The thermal transfer composition relates to a fluoropolymer coating composition, which can be used, for example, to coat electrodes and/or membranes in electrochemical devices. The fluoropolymer coating composition preferably contains multiple fluoropolymer phases. The coated electrodes and/or membranes exhibit excellent wet adhesion, excellent dry adhesion, and low leachable. Each fluoropolymer phase contains a polymer with a mass fraction of at least 10% of a common fluorinated monomer, thereby ensuring compatibility among the polymer phases and allowing these phases to be distributed quite uniformly at a macroscopic level throughout the composition and in the dried coating formed from the composition.

Permeable fluorine ion exchange resin dispersion:

The micelle particle size of the resin dispersion is 145 to 210 nm, exhibiting the advantages of uniformity and stability. The operating temperature of the catalytic layer prepared with this dispersion can be extended from 30 to 85 °C to 30 to 150 °C. A portion of heterocycles is introduced into the structure of the fluorine-containing ion exchange resin, which has a larger steric hindrance, resulting in a decrease in the crystallinity of the polymer and an increase in permeability, making it particularly suitable for application on catalyst coating resins, effectively reducing the impedance of the catalytic layer and enhancing the performance of the fuel cell. Furthermore, the development of thermal transfer compounds also involves matching lubricants, such as polyol esters (POE) and polyethylene glycols (PVE), to ensure the proper operation of compressors in refrigeration systems and to extend equipment lifespan. The formulation of these compounds requires precise adjustments to accommodate varying working temperatures, pressure conditions, and system designs, thereby enhancing overall system reliability and efficiency. As we can see, the thermal transfer compositions mainly focus on optimizing thermal transfer efficiency, and also on being environmentally friendly, like reducing global warming potential (GWP) and ozone depletion potential (ODP).

5. Application of thermal transfer compositions

5.1. Thermal Management of Electronic Products

With the development of electronic devices towards higher performance and miniaturization, the heat generated by internal components continues to increase, leading to excessive temperatures that can affect performance and shorten lifespan. Traditional cooling methods such as fans or metal heat sinks have become insufficient to meet the demands [4]. The remedy lies in the utilization of thermally conductive silicone grease, a material employed to fill the minute gaps between electronic components and heat sinks. Serving as the interface material between the CPU/GPU and the heat sink, its objective is to diminish contact thermal resistance and enhance overall heat dissipation efficiency [5]. This silicone grease incorporates high thermal conductivity particles, including silver and aluminum oxide, which are capable of effectively filling the minuscule gaps between the two. By doing so, it reduces contact thermal resistance and thereby improves overall heat dissipation efficiency. By utilizing efficient thermal transfer compositions, only has the operating temperature of critical components been reduced, but the stability and reliability of the system have also been enhanced. Furthermore, due to the decrease in failure rates caused by overheating, maintenance costs have been indirectly lowered.

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5.2. Optimization of air conditioning and refrigeration systems

The efficiency of heat exchange between the condenser and evaporator within an air conditioning system directly bears upon the energy efficiency ratio of the entire system. Although certain extant copper tube fin heat exchangers possess favorable thermal transfer performance, they are large in size and heavy in weight, which is not conducive to lightweight design [6]. A compact microchannel heat exchanger made of a new type of composite material has been developed [7]. This material amalgamates a high thermal conductivity coefficient with excellent corrosion resistance. Moreover, the design of the internal microchannels augments the heat exchange surface area per unit area, thereby permitting enhanced heat exchange efficiency under identical conditions. The novel heat exchanger is not only smaller in size and lighter in weight, but its heat exchange efficiency has improved by approximately 10% compared to traditional products. This not only helps save installation space but also reduces manufacturing costs and transportation expenses. More importantly, it provides technical support for the development of the next generation of energy-efficient air conditioning systems.

5.3. Thermal Protection of Aircraft Engines

Aerospace engines are required to withstand severe temperature fluctuations in high-altitude environments. Advanced composite materials, in conjunction with efficient heat dissipation designs, are essential to ensure the engines' safe and reliable operation [8]. However, thermal shock under extreme conditions remains a significant challenge. The solution involves a combination strategy utilizing multi-layer insulation (MLI) along with ceramic matrix composites (CMC). MLI consists of multiple layers of thin films that effectively block external heat intrusion, whereas CMC is employed in critical areas such as combustion chamber walls due to its excellent high-temperature stability and low-density characteristics [9]. Upon testing and verification, this combination of thermal protection measures can reduce the surface temperature of the engine by up to 200°C. This significantly enhances the durability and fatigue resistance of components. At the same time, it reduces structural weight and improves the overall performance of the aircraft. The above cases demonstrate the successful application of thermal transfer compositions in various fields, which not only address the thermal management challenges they face but also bring significant technological advancements and economic benefits.

6. Current challenges and future prospects

Although thermal transfer materials have made significant progress in various fields, their further development continues to encounter a series of challenges at the technical, economic, and social levels. Thermal transfer compositions face numerous challenges, including interface compatibility, long-term stability, multifunctional integration, cost-effectiveness, environmental and social factors, and standardization construction. The intricate interactions at the interface between materials can give rise to increased contact thermal resistance, necessitating a profound comprehension of physicochemical properties and the implementation of effective surface treatment technologies. Long-term stability is crucial for large-scale applications, and multifunctional integration is difficult to achieve within the same material system. High-performance fillers and advanced matrix materials are expensive and require significant equipment investment and operational difficulties. Environmental and social factors involve the demand for green and sustainable thermal transfer compositions, promoting a circular economy, and standardization construction to improve product quality. Future research ought to center on innovative materials, such as intelligent responsive materials that can adjust thermal conductivity characteristics based on temperature changes, and sustainable development concepts like green manufacturing, promoting a circular economy, and

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reducing waste and pollutant emissions. Despite these challenges, advancements in science and technology and collective efforts from various sectors of society may demonstrate broader application prospects and development potential in the future [10][11].

7. Conclusion

Through a meticulous and comprehensive review of thermal transfer compositions, this paper delves deeply into the research advancements within domains such as material selection, performance optimization, and application prospects. Ranging from fundamental theoretical underpinnings to practical case analyses, it clearly demonstrates how these composite materials play an irreplaceable role in various high-tech fields through clever design and innovative applications. Regarding material diversity, thermal transfer compositions are not limited to traditional metal-based or ceramic-based materials but also include polymer-based, nano-reinforced composites and other types. Each material has its own unique physicochemical properties and is suitable for different application scenarios. Furthermore, in the aspect of performance achievements, by integrating high thermal conductivity fillers like carbon nanotubes and graphene, optimizing interface structures, and creating novel preparation processes, researchers have significantly improved the thermal conductivity and other crucial performance indicators of the materials. This enables thermal transfer compositions to maintain efficient and stable thermal transfer capabilities over a wider temperature range. Nevertheless, this paper is not without its flaws. Firstly, due to the incomplete citation of data in this article, there may be instances where this article appears unprofessional and insufficiently developed. Secondly, due to a relative lack of expertise, my article may contain erroneous judgments regarding current challenges and future prospects, as well as biases in the examples provided. Thirdly, due to the rapid advancement of scientific research, some of the cited data and conclusions may have changed with new discoveries. To address these issues, I need to study the relevant knowledge more diligently while continuously practicing, conducting research, and engaging in other activities to broaden my professional knowledge base, thereby enabling me to write a more comprehensive and accurate thesis.

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